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A review of planning and operational models used for emergency evacuation situations in Australia

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Abstract

Thos paper focuses on planning and modelling bush fire-related evacuation, which is perhaps the most difficult disaster situation faced in Australia. It includes a discussion of the available data and the current Australian methods for analysis and planning. The paper concludes with a specification of the needs for models related to advance planning for potential emergencies (largely for bush fires) and for operational models for tactical application in dealing with emergencies, either in simulation exercises or in real circumstances. This includes the identification of critical locations in road networks. There has been some research on the development of a dynamic stated choice procedure for evacuation decision making under bush fire events, but much more research is required. The stated choice procedure could include visualisation to enhance the presentation of alternate scenarios.

Keywords: bushfires; evacuation policy; road network; scenario planning; strategic planning; models

1. Introduction

Emergency evacuations in Australia generally occur in the face of natural disasters, most commonly for bush fires (wild fires), then floods, and occasionally cyclones (elsewhere known as hurricanes or typhoons). The cyclones have been limited to the tropical northern third of the country, but in the face of global warming meteorologists predict that cyclone activity will move to the south and the more settled coastal regions. Climate change and global warming is also likely to increase bush fire threats, exacerbating the situation in the peri-urban areas currently subject to considerable demographic change and new settlement. Historically there are only limited cases of emergency evacuations due to man-made disasters, with the exception of fires in buildings – which are events of limited local impact as opposed to the wider impacts of the natural extreme events. Australia is to a large extent geologically stable so that earthquakes are quite rare, while its climate means that blizzards are almost unknown, except in remote alpine areas.

Thus the main focus of the paper is on planning and modelling bush fire-related evacuations. There are a number of reasons for this. Firstly, the bush fire is the most lethal of the three natural disasters and affects the more

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populated south eastern and south western corners of the country, with exurban and peri-urban areas of the major cities subject to bush fire risks. Cyclones are confined to the tropical areas in Australia's north, which are much less populated. Floods, whilst the most common of the natural disasters, are largely confined to well defined, low lying areas and good predictive tools are available. Advance warning systems for floods and cyclones are in place, providing emergency service agencies with a much greater level of confidence in prediction of potential trajectories and intensities for those disasters than is possible with bush fires. There are, of course, still many stochastic factors that may intervene in all of these cases.

The short term dynamic nature of bush fire evolution, progression and movement means that advance planning for specific circumstances is much more difficult. Ignition points for fires are largely random. Once it has started the movement and intensity of a fire is strongly affected by wind speed and direction, temperature and humidity, and topography and vegetation, and so fires can change course rapidly. There are operational models for predicting the movement of fires, but the application of these is limited 'in the heat of the moment'. The emphasis is therefore on the development and testing of emergency scenarios from which 'fire action plans' can be determined. These plans cover police, fire fighting, emergency and transport services. They also cover local government agencies, communities, and individual households resident in 'fire prone' areas. On this score there is a degree of controversy. It is well established that the worst situation that an individual can put themselves in during a bush fire is to be outside, either in a vehicle or on foot. In some states of Australia, notably South Australia and Victoria – which due to their Mediterranean-type climates have perhaps the longest histories of dealing with bush fires – household fire action plans will include options for residents to remain in their houses during a fire (albeit under carefully prescribed conditions). The principle is that 'the house will protect you as the fire front approaches, and once the fire front has passed you can protect your house by moving outside and extinguishing spot blazes and smouldering embers'. But the application of this principle needs the residents to be physically and mentally prepared, and fully versed in what to do and the need to avoid last minute panic. In other states, police and emergency services can direct residents to evacuate, although the final decision has to be made by the individuals. The models associated with each of these two emergency planning alternatives are therefore different. Recent catastrophic events have, to coin a phrase, reignited the controversy. Climate change and global warming are adding to the complexities, due to increased fire risks in terms of spatial and temporal dimensions, and the intensity of the disaster events. For transport planners and road network managers, there are unresolved questions about the utility of existing peri-urban road networks to cater adequately for evacuations.

The definition of 'model' adopted in this paper is a broad one. For transport analysts a 'model' is commonly seen in the narrow terms of a set of mathematical equations, logical relationships and computational algorithms which are used to calculate a set of numerical outputs. This may be paraphrased into the definition of a 'mathematical model' as a numerical procedure that transforms a set of known data into (estimates of) desired but otherwise unknown information. Models may also be seen more broadly as processes that describe a particular system and its operation, and that can indicate how that system may be altered to work more efficiently, inclusively, or productively. It is this broader perspective of the process model that is used here. The process model includes the genre of mathematical models, but also encompasses the more qualitative aspects of system composition, description and operation.

2. Review of practice and models

The basic process model used in Australia is 'stay or go'[b]. This' policy is in use in all the states and territories of Australia (although the implementations may differ), and was developed and adopted in the light of research conducted after the major bush fires in South Australia and Victoria in 1983. It is basically the decision to be made by individuals as to whether they stay and defend their properties or evacuate early. The policy stresses that people choosing to stay and defend must be properly equipped and physically and mentally prepared to do so, and then remain in their houses/shelter until the fire has passed. There are also conditions on how the property must be defended. One of the biggest dangers to human life is to choose to stay but then panic and evacuate later on.

In South Australia the Country Fire Service (CFS) has two types of warning systems. The first is an information message which informs residents of a potential threat due to bushfire. The second is a warning message, preceded by

[b] More precisely, 'prepare, stay and defend, or go'.

a warning signal which is given when a bushfire is out of control in severe weather conditions and poses immediate threat to the public. This second warning 'requires an immediate response from the public to ensure their safety and survival' [1]. With the aim of maximising coverage, specific bush fire warnings are broadcast on the radio stations of the Australian Broadcasting Corporation. Residents are warned to have battery powered radios and to listen to the relevant radio station in their locality.

The CFS, along with other country fire services such as the Country Fire Authority in Victoria, say that the decision of whether to stay or go should be made well in advance of any fire. Households should have their own fire action plan ready before the bushfire season starts, and the fire services provide 'self help' kits for households to use in developing their plans. If the decision is to stay there are various precautions that should already be in place, and if the decision is to leave early the CFS suggest having a relocation kit handy. Suggested contents of the relocation kit include blankets, water, first aid kit and medication and provisions for pets. For preparation to stay and defend, regular site maintenance is required. Bushfire material should be removed from gardens; this included dead branches, leaves and undergrowth. Branches more than two metres high or that overhang the house need to be pruned, and flammable material such as mulch, long grass, bark and wood piles removed from the proximity of dwellings and sheds. In addition to these preparations there are recommendations for the installation of sprinkler system to wet the garden, reducing its impact to radiant heat, and have access to an alternative water supply (e.g. a pool) with a petrol driven water pump in case mains electricity is cut off [1]. These are just a few of the suggestions and there are many other preparations that can be undertaken to help protect a property. After the preparation of the property you must shelter in the building until the fire has passed and then go outside and put out any embers or sparks that have caught on your home. Panicking at the last minute and trying to evacuate is extremely dangerous. Radiant heat is one of the biggest killers in terms of bushfires so to be out on foot or in a vehicle during the bushfire is very dangerous. Also, driving in this situation is dangerous due to a number of factors. Firstly the smoke can reduce vision so makes it more likely that the driver will not see a fallen branch or emergency vehicle or some other vehicle until it is too late, causing a crash. Secondly, as mentioned above the car is not safe in terms of radiant heat. Thirdly, due to the panic the driver may not drive as carefully as usual which also increases the risk of a crash. Fourthly, they may come across a closed road and have to turn around giving them even less time to escape the firefront.

Figure 1, from [2], indicates the main areas of bush fire risk in Australia. These areas are primarily in the populated south east and south west corners of the continent. They are characterised by a Mediterranean climate with prolonged dry summers, areas of forest close to human settlements, and increasing peri-urban populations as people seek changes in lifestyle and environment. The key to this figure includes an assessment of the risk of extreme fire weather. There is now evidence that the occurrence and risk of extreme fire weather is on the increase (e.g. [3]), so that the 'extreme' and 'very high' zones shown in Figure 1 are increasing in size and distribution – and this will accelerate under the prevailing climate change scenarios.

Haynes et al [4] discussed the development of a database of Australian bushfire civilian fatalities, which was created as part of a larger database of Australian natural hazards. This database looks at deaths, causes and locations. It includes 552 records over the past 100 years, from 1900 to the 2007/08 bushfire season. According to [4], 82 per cent of civilian deaths from bushfires since 1900 have been from flames, heat and smoke inhalation. They also suggested that about 32 per cent of deaths are from late evacuation, followed by approximately 26 per cent of deaths from being outside defending the property and eight per cent being inside a defensible property. However most of the eight per cent comes from people passively sheltering inside the property rather than having taken the above precautions to defend the property. Evidence from Hobart 1967 and 'Ash Wednesday' in 1983 shows that radiant heat or vehicle accidents while evacuating were killing civilians and that a well prepared house could be saved and be a safe refuge for civilians. The data shows that over time there has been a decrease in the overall number of deaths due to bushfires but an increase in the number of deaths during evacuation. These findings were supported by [5], which considered the economic costs of natural disasters in Australia.

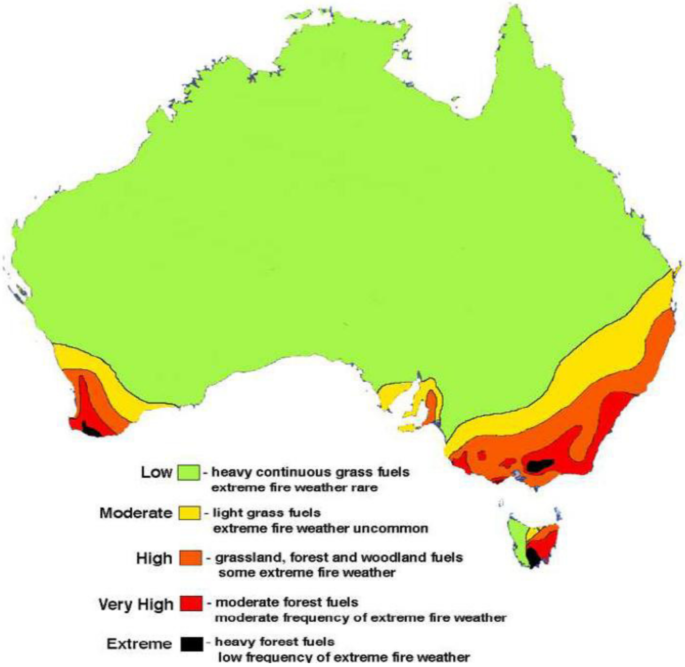

Figure 1: Bushfire risk in Australia [source: [2]]

The general policy in place in Australia regarding bushfire evacuations may be summarised by the recent position statement on evacuations issues by the Department of Environment and Conservation in Western Australia [6]. This position statement emphasises that the department and associated Hazard Management Agencies (HMA) have responsibility for the protection of life, property and the environment from fire and will make decisions in relation to community dangers posed by bushfires. The WA Police Service has an obligation for the protection of life and property. Agencies with fire management related responsibilities and the Western Australia Police Service will work together to protect life and property during bushfires in the best interests of the community, on the basis of the following principles:

1. where adequate fire protection measures have been implemented, able bodied people are encouraged to remain in their homes during the passing of the fire front
2. where adequate fire protection measures have not been undertaken, the occupants of houses should relocate to a welfare centre (or other safe area) well before the approach of the fire, for their own safety
3. a police officer will seek the advice of the operational Incident Controller (IC) prior to organising an evacuation. However, when loss of life or injury is imminent, and a decision from the IC is not readily available, a police officer may make a decision to evacuate. Mass evacuation is not the favoured option
4. road closures must be determined by the HMA to ensure public and emergency personnel safety, such that:
    - the IC will determine the location and timing of any road closures
    - roads will be closed before they become unsafe and will remain closed until the IC determines that they have returned to a safe condition
    - when loss of life or injury is imminent, and a decision from the IC is not readily available, a police officer may make a decision to close a road with immediate notification to the IC
    - while roads are closed, every effort should be made, in consultation with the IC, to safely escort able bodied residents to return to their homes as soon as possible as they may be needed to protect their homes from ongoing ember fires.

3. Bushfire prediction models

The intensity and speed of bushfires are related to the amount fuel (e.g. dead vegetation), the moisture content of this fuel, wind speed, and topological factors such as the slope of the land. It is important that bushfire behaviour can be modelled so that steps can be taken to reduce the risk of damage, such as prescribed burning and planning how to manage and suppress the fire should it occur. In Australia we use empirical models of bushfire behaviour that are based on the statistical correlations between various factors that present a danger in bushfires [2].

3.1. Wildfire Threat Analysis

Wildfire Threat Analysis (WTA) is a model developed to estimate the risk of a wildfire in selected areas. There are four categories of information, each represented on a map, and then these maps are overlaid to determine the risk. The assessment of this risk can help evaluate the negative ecological, social and economic impacts of wildfire [7]. It is an analysis of spatial patterns of hazard, risk of ignition and natural and constructed values, and how they interact to determine the threat of wildfire across the landscape [8].

The first category is values at risk. This can include factors such as population, property and natural resources. It maps data associated with human life, communities, watersheds/soils, natural resources, and infrastructure. The second category is the likelihood of a wildfire occurring. This is a map showing which areas are of high, moderate or low risk of ignition and some of the information for this comes from the recent history of fires in the area. The third category is the ability to mount a fire suppression response. This involves the time taken to detect a fire and the time it takes for fire fighters to reach the fire and set up an appropriate line of defence. The times are purely relative, not exact, and are represented by classes ranging from ‘poor’ to ‘immediate’. The maps in this category include lookout tower visibility, air tanker response time targets from air tanker bases (ground based). Air bomber response time targets from skimmer lakes and steepness of slope [7]. The last category is the headfire behaviour, or the potential wildfire intensity. The behaviour of the fire is estimated by the use of the Forest Fire Behaviour Tables. These tables were set up based on empirical data taken from both experimental and wild fires in the respective areas and takes into account wind speed and surface moisture to determine the rate of spread (referred to as the Fire Danger Index, FDI) for standard fuel conditions. The FDI can be adjusted for other fuel conditions also. The table has now been converted into a series of equations to assist in their usage. In this category the rate of spread of the fire along with its intensity are calculated based on the fuel type and quantity, wind, slope and weather. These divide the headfire into five classes which define the defending responses which may be appropriate to fight the fire. These five classes are: direct attack on headfire front not possible, ground attack on headfire not possible, machine attack possible, hand attack feasible, and readily suppressed [9].

One of the strengths of WTA is that it gives a structured presentation of all factors that contribute to the wildfire risk. It also provides a tool for decision making and can explain the rationale behind fire management decisions. One of the weaknesses is that it does not quantify the risk and so is unable to compare the overall risk between any two areas ([9]. And while it does take into account the landscape, based on GIS data, it does not take into account changing time so it can be used for risk assessment, but not so much for management of a fire as it is occurring. It is used by fire managers to make strategic decisions about where to locate resources that can be used in the event of a fire in order to suppress it.

3.2. Phoenix

Phoenix is a model that is being developed by the Bushfire Cooperative Research Centre for use in southern Australia and it makes up one part of a bushfire risk management model. It is a scenario based model where users can input a scenario and the model will output the likely consequences. Phoenix has three components: a fire management business model, a fire characterisation model, and a fire impact model. Each of these three components is discussed individually.

The fire management business model is used to develop the context of a risk management process and can then be used to look at the strength and type of interactions between differing elements of bushfire management. These elements are divided into five strategies covering fire management activities: prevention, preparedness, response, recovery, and fire regime management [10]. Phoenix looks at the relationships between this business model and the impacts and consequences of bushfires in the landscape through the rate, intensity, frequency, and size of spread of the bushfire. The inputs to the model are various environmental, physical and meteorological aspects such as fuel types and disruptions, fire history, topography, assets and values, road proximity, wind and weather factors, and suppression resources. The outputs of the model include the origin of the fire, the extent and intensity of the fire, its frequency, flame height, area covered, time to impact, and spotting. It creates a fire grid and with this uses models of fire behaviour and fire perimeter propagation to produce the outputs. The business model can quantify the relationships between the different elements and can show the strengths between these relationships in terms of cost and the ability to reduce the risk of the bushfire. It is a non-spatially explicit bushfire risk mitigation model.

The fire characterisation model in Phoenix can take in changes to fuel, weather, and topographic conditions as the bushfire increases in size and spreads across the landscape. There two models that are used and modified to assist Phoenix in this characterisation model; the CSIRO southern grassland fire spread model and the McArthur Mk5 forest fire behaviour model. The fire characterisation model is used to calculate the point rate of spread, flame height, and fireline intensity. The landscape is divided up into equally sized square cells and each cell has its own set of attributes for both inputs and outputs from the simulation. Huygen's fire spread algorithm is used to translate how the fire behaviour at each point around the perimeter of the fire then spreads across the landscape. The attributes of the cells are then stored in a database where they can be analysed. Phoenix also incorporates a number of models for various environmental and landscape factors to assist in determining the movement or extinction of the fire perimeter from one time period to the next.

The fire impact model is used to calculate an estimate of the physical impact of the bushfire on predetermined values and assets. This provides information to asses the consequences of these impacts and the spatially and temporally explicit output from Phoenix can be used to estimate the nature and degree of the impacts of the fire. From this a set of potential impact curves can be drawn up, for example to see how many houses may be lost due to the fire. Changes to the business model can then lead to changes in the impact curves in the fire impact model and so this can be used to assist in decision making for fire management.

The strengths of this Bushfire Risk Management Model are the provision of an objective basis for evaluating various fire management options and that it quantifies the level of impact on an array of values and assets. Also, unlike in WTA described above, it is not based on static inputs or subjective weightings. A weakness is its reliance on good quality input data of environmental and meteorological conditions. One of the major benefits of GIS based modelling is that Phoenix gives visual as well as analytical results.

3.3. McArthur indices

The McArthur Forest and Grassland Indices have been set up to try to indicate how difficult it would be to suppress a fire occurring on that particular day. The McArthur Forest Fire Danger Meter was first used in 1967, and was based on the results of over 800 experimental fires and wildfire observations [11, 12]. It was then updated in 1973 to the current meter used. The forest index is based on a fire burning in high eucalypt forest and is used to look at the behaviour of the fire. The index ranges from 1 to 100, where a rating of 1 means that a fire will not burn and a rating of 100 means that the fire will burn extremely quickly and will be near impossible to suppress. This fire danger meter is in use by all fire authorities in Australia except for Western Australia, and also by the Australian Bureau of Meteorology.

The Grassland Fire Danger Meter is similar to the forest fire danger meter except it is used for grassland, such as pastures, rather than eucalypt forest. In the early summer in southern Australia the meter uses the common pasture condition, however by the late summer, or during drought conditions, the fuel load will be greatly reduced and so would actually help with fire suppression [13]. The grassland meter gives an indication of the risk of a fire starting, its rate of spread, the difficulty of controlling the fire, and the amount of damage it could do.

The inputs that go into the grassland meter are air temperature, relative humidity, degree of curing and wind speed. For the forest meter the inputs are rainfall, drought index (Byram-Keetch drought index and soil dryness index), air temperature, relative humidity and wind speed [2].

There are five fire danger ratings with these indices: low, moderate, high, very high, and extreme. These meters are used for public information / warnings, and to help decide whether there is a requirement for a fire ban that day. One issue with these meters is that an error in the weather forecast will produce an error in the actual risk indicated by the meters.

3.4. Blanche scale

The Blanche scale [14] was developed as an alternative metric for reporting the magnitude of a bushfire, given that the magnitude can be dependent on the reporter and the extent of the information received. This scale provides a fire rating of on a scale of 1-5, where rating 1 is for a mild bushfire that is progressing slowly and usually only has one ignition point and rating 5 is for bushfires of extreme severity (which spread quickly and generally have multiple ignition points). These severe fires usually occur when there are high temperatures and high wind speed.

3.5. Evacuation behaviour modelling

Alsnih, Rose and Stopher [15] looked at evacuation of households in a bushfire. They listed three types of evacuation; mandatory, recommended and voluntary, however they indicated that in the case of a bushfire it is known that people do not like the mandatory evacuation – they would rather make their own decisions about it. Evacuation time was defined as consisting of the response time, decision time, notification time (in the case of mandatory evacuation) and preparation time, in keeping with the Sorensen model of evacuation behaviour [16]. The researchers sought to develop a model of evacuation behaviour that would predict the proportions of the population that would leave within certain time periods, thus leading to the development of an evacuation travel demand model. There are many factors that affect the decision of whether to evacuate or not and these include, but are not limited to, demographic characteristics, risk sensitivity, social ties, information and perceived threat. In order to model evacuation behaviour a stated preference survey was carried out with residents who had been affected by bushfires. From this data set a mixed logit model was developed, which (1) indicated the probability that a household decision maker would choose to stay, or initiate a full or partial evacuation of the household, and (2) estimated how many partial and full household evacuations will take place by time interval from when the emergency is first perceived.

The resultant model produced some interesting implications:

- the more vehicles owned by a household, the less likely that the household would undergo a full evacuation
- older decision makers were more likely not to evacuate
- female household decision makers were more likely to evacuate that male household decision makers
- households with young children were more likely to stay than those without children (a counter-intuitive result)
- households with elderly members were more likely to evacuate
- long term residents of an area were less likely to evacuate than those with short periods of residency
- in terms of environmental characteristics, fuel load (or the period since the last fuel load reduction) was the factor most likely to trigger a decision to evacuate.

Discrete choice modelling for evacuation modelling is also reported in the international literature. Fu and Wilmot [17] developed a sequential binary logit model of departure time choice in evacuations due to hurricanes in Louisiana, while Mozumder, Raheem, Talberth and Berrens [18] developed a bivariate probit model for evacuation decisions for peri-urban residents in New Mexico. More generally, Russo and Chila [19] argued for the inclusion of stated preference data along with revealed preference data in the development of behavioural models of road evacuations in emergency situations. This methodology is important in the development of planning models for evacuation behaviour – see also [20, 21].

4. International perspectives and practices

In Finland there is research being done into a spatio-temporal model of population location with the aim of improving risk assessment and damage analysis. The reason for this research is the fact that current models do not take into account the variation in the location of the population during different times of the day. This is being done to assist in the preparation planning and decision making under various scenarios. It is intended for the long term planning of risk assessment and damage analysis rather than the short term emergency response when there is an outbreak of fire. Currently the Finnish Fire and Rescue Services use a Geographic Information Systems (GIS) model that creates a risk zone map based on the population, the floor area in square metres, and an index for the probability of a road crash [22]. In this case the model is more for building fires in urban areas, rather than bushfires, and is used to assist the decision maker in resource and evacuation planning, however it has the potential to be applicable to bushfires in Australia as the time that the bushfire begins will affect the potential use of the 'stay or go' policy.

Along with Australia, Canada, the USA and most Mediterranean countries are also prone to bushfires. Arnol [23] reported on a study tour to the USA, Spain, Portugal, France, Italy and Greece, which he undertook to learn about their practices of bushfire management for urban interface (UI) fires and to see how Australia could learn from them. The following is a summary of what he found in each of the countries visited.

The urban interface (UI) zone is where houses are on the edge of bushland and hence are at high risk during a bushfire in that area. With more and more people moving to these areas and the spread of the urban space the UI zone is increasing in size / distance.

Out of the countries visited France was the only one where, similar to Australia, residents are encouraged to stay and defend their properties and shelter in them. In all other countries there exists mandatory evacuation of residents.

In the USA local government authorities are responsible for the emergency services in their area, but the state, city, county police and federal forest and park authorities are also involved. Generally there is a chief that is in charge of an 'integrated incident command team' and they all work together to fight the fire. In Portugal and Italy it is the Civil Protection Authority that takes charge in major emergencies at both local and regional levels, while the Forestry Department is responsible for the forest fires but can call on urban firefighters to fight the fire on the UI. Here the agencies coordinate their responses from their own operating rooms. In Spain the Fire Service is a part of the Civil Protection Authority, whereas in Greece and France the Fire Services are individually responsible for all firefighting [23].

Arnol also indicated that firefighting services in US counties require residents on the UI to clear a certain amount of land around their homes . Also, the US fire authorities develop plans for firefighting on the UI and use such data as wildfire hazard, access, briefing points, evacuation management, safe areas, water availability and tactics to be used. Most of the countries visited had mapped the UI and determined what areas need to be cleared, or had even restricted building in dangerous areas. They then have plans developed for how to best fight the fire and the operations and organisations employed to do so. Pre-planning is the dominant feature of the bushfire management process.

US policy is largely to seek evacuation of threatened populations, although expert evidence presented to the Victorian Bushfire Royal Commission [24] suggested that compulsory evacuation is seldom enforced in most states. Consideration of alternative policies, notably the Australian 'stay or go' policy – expressed more properly as 'prepare, stay and defend, or leave early', was discussed by Paveglio, Carroll and Jakes [25], who concluded that:

- remaining inside fire-safe structures or at designated safety zones to actively defend against wildfire events is an area of research that needs considerably more attention in the American context
- 'shelter in place' during wildfires demands a more active view of participants in ensuring their safety
- the Australian model of fire response – 'prepare, stay and defend, or leave early' – could be considered as a viable alternative to evacuation in some, but not all, urban interface fire situations.

5. New circumstances – February 2009

The generation-long accepted model for bushfire management and evacuation in south east Australia was severely tested and perhaps found wanting in early 2009. A severe weather event, the exceptional January-February 2009 heatwave, culminated in the massive 'Black Saturday' bushfires that ravaged the state of Victoria on 7 February. The heatwave was notable for both its intensity and duration. Melbourne recorded its hottest ever day (from 154 years of data records) on 7 February 2009 (46.4°C), exceeding the previous maximum of 45.6°C on 13 January 1939. Three of Melbourne's five hottest days on record occurred during the heatwave. Adelaide equalled its 1908 record with six consecutive days above 40°C, and both Adelaide and Melbourne set new records for the most consecutive days above 43°C – Adelaide four days, 27-30 January, and Melbourne three days, 28-30 January[c] [3]. The Black Saturday fires claimed some 173 lives and completely destroyed a number of towns and villages [24].

[c] The previous record in both cities was a mere two days each.

Figure 2 shows a true colour satellite image of south eastern Australia at about 3:00 pm Australian Eastern Daylight Savings Time (AEDT) on 7 February, in which the smoke plumes from a number of fires, including the major 'Kilmore fire', are clearly visible.

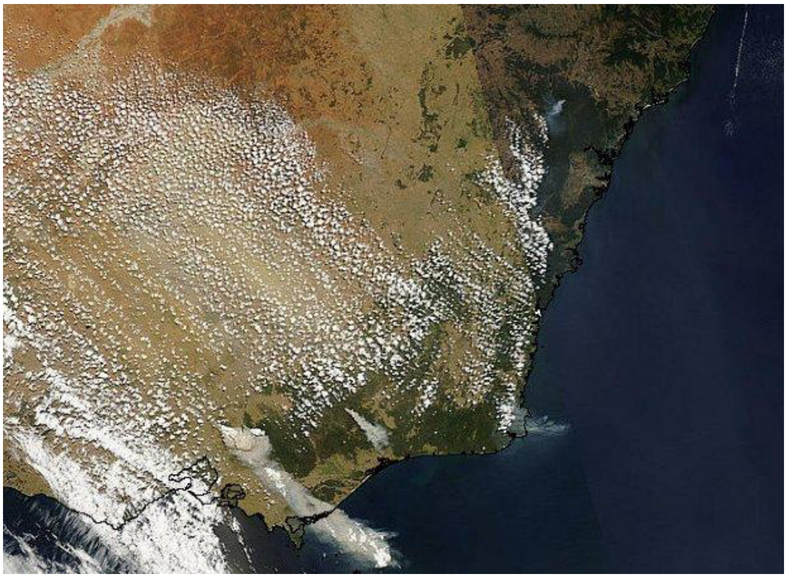

Figure 2: True colour imagery from the US MODIS Aqua satellite at about 04 UTC (3 pm AEDT) on Saturday 7 February 2009, showing the smoke plumes from fires, including the dense cloud column ascending to high altitudes from the Kilmore fire [source: [26]]

What actually happened on Black Saturday is the subject of a current Royal Commission investigation, although the commission has issued an interim report [24]. The 'stay or go' policy is under special investigation. Some 113 of the fatalities appear to be people who had stayed in their homes. There is evidence that many of these people were physically able and had made the previously accepted provisions in terms of preparations and equipment to defend their homes. It may be conjectured that the deficiency perhaps lay in psychological capacities to deal with a fire threat of previously unimagined magnitude and severity – the FDI values for the fires exceeded any previously recorded values. Those caught in the open were often in vehicles attempting to navigate along narrow rural roads, with falling trees and visibility restricted by smoke, and in a confused state with vehicles moving along these roads in both directions. As can best be established after the events, collisions between vehicles (travelling in the same or opposite directions), and with fixed objects on or near the road, seem to have been common. The state and use of community information and warning systems form another area of interest for the Royal Commission.

The interim report of the Royal Commission [24] indicates that a revised process model will be recommended. Whilst the 'stay or go' policy will remain, modifications will be made, especially in terms of the emphasis of the policy and the provision of information to the public, for example:

- the content of bushfire warnings should be designed to maximise the potential to save lives and minimise the risk of loss and damage
- an improved system of warnings must be developed. This system should:
    - provide a clear description of where the fire is and where it is predicted to travel, including by reference to wind change if relevant: a fire and the direction in which it is travelling should be described by reference to local features and in a manner which enables a resident, traveller or visitor to ascertain the fire's location and its likely path and, where possible, the predicted time of any wind change

  - include the time expected before impact of the fire on particular communities, with times provided in a simple AM / PM format and wherever possible the time or window of time in which a fire is expected to reach particular towns or communities should be specified
  - use warnings that are drafted using direct and clear language, and avoid which euphemisms – for example reference should be to 'you' (rather than 'residents') and 'homes and farms' (rather than 'properties')
  - for the longer term, employ a clear means of communicating the severity of a bushfire, perhaps drawing on the 'category 1, category 2, etc' terminology used for cyclone warnings. Such a scale might usefully draw on a revised FDI scale applicable to extreme fire danger
- develop a 'stay or go' policy that focuses on residents leaving early during a bush fire, with the general advice that the safest way to survive a bushfire is to leave early
- include a website tool that enables householders to decide a property's risk level
- use social websites such as 'Facebook' and 'Twitter' to carry fire warnings
- inform and educate communities about the safest place to go in neighbourhoods during a fire
- develop individual protection plans for high-risk settlements
- require the fire services to develop programs to actively advise individual residents in bushfire-risk zones about the defensibility of their properties
- provide clear advice in planning for evacuations when to leave, where to go, and the routes to use, as part of the development of fire management plans.

The question arises: how can transport research contribute to a better process model for planning for emergency response to bushfires?

6. Needs for modelling tools – problem definition

Consideration of transport models for emergency situations in rural areas is not a new development. Models were being developed in the 1980s, for example [27] provided a specification for rural area evacuation models, and indeed a prototype model. On the basis of the Radwan-Hobeika-Sivasailam framework [27], but taking account of the developments in computer and information technologies and transport modelling techniques over the last quarter century, a model specification can be written as follows. For a simple macroscopic model that can provide planning guidance for the evacuation of people from threatened areas to safe designated shelters outside or inside the threatened area, the following model specifications can be applied:

- the simplicity of the model should not be achieved at the expense of reliable results and appropriate detail
- the model should be dynamic in updating both the state of the emergency and the levels of road access, traffic conditions, volumes, travel times and (if appropriate) queuing
- the model needs to include and provide realistic measures of intersection, link and network capacities. This must include specific realisation of the capacity and characteristics of traffic flow on two-way two-lane roads with restricted sight distances
- the model requires the capability to evaluate the impacts of future land use plans and population distribution and intensity on evacuation times and rates
- the model must include good representation of the behaviour of individuals
- the major application of the model is for strategic planning, based on scenario studies for different natural disasters (including intensity and location) under a range of environmental and meteorological conditions
- the model's outputs will be used to inform and assist the strategic planning processes in a locality, in conjunction with local knowledge and available professional expertise
- the model should be developed in a dynamic GIS software platform, including and integrating accurate road network, terrain and topography, land use and population, and vegetation, environmental and meteorological databases.

The vital position of dynamic GIS as the underlying software platform support for the model has already been identified, e.g. [22, 28]. Given the existence of comprehensive and accurate data on physical characteristics (e.g. terrain, topography, vegetation and environment), demographics and land use, infrastructure and facilities (e.g. road networks, water supply and electricity distribution), the GIS platform provides the means to integrate the databases and to host the different computational models. In addition, the road network model attached to the GIS is used to determine both shortest paths from inhabited zones to shelters and also 'second-best' paths. Similar path calculations would be made for use by emergency services when seeking to reach any specified locations. Path determination is done initially for the normal, full and intact network as the base case.

Disaster scenarios may then be simulated for different scenarios, using (in the case of bushfires) a model such as Phoenix, to be run with different meteorological conditions and fire ignition points. The paths and impacts of the simulated fires can then be used to determine the likely consequences for the road network. Sohn [29]has, for instance, used a similar approach to establish vulnerable links in a regional road network subject to flooding. In the case of bushfire modelling, the analysis would be undertaken from two perspectives. First would be the identification of likely 'weak spots' in the road network, being links and road sections most likely to be affected (i.e. degraded or closed) by fires. Second would be the identification of resilient links and road sections, being those parts of the network least likely to be affected by fires. That is, both network vulnerability and network resilience are important considerations. Outputs from the model would include qualified advice about most reliable evacuation routes – and access routes for emergency services. Qualification of the advice is necessary because of the significant stochastic variations in circumstances inherent in the natural disaster scenarios, e.g. [30, 31].

Traffic movements on rural road networks need to be studied and modelled with care, because of the unique nature of traffic flows on such roads. On this score recent developments in traffic flow modelling for two-way, two-lane roads should prove useful in providing the necessary macroscopic traffic modelling capability. In particular the recent research in France [32] and in The Netherlands [33] is most useful.

The identification of vulnerable links in a network can be undertaken using the recently developed methods for network vulnerability analysis and the determination of critical locations, as described in [34, 35, 36, 37]. Modifications to the approach can be made to identify the most resilient links as well as the most vulnerable ones. It is likely that a combination of the criticality and importance metrics introduced by Jenelius, Petersen and Mattsson [33] and the area-accessibility-based vulnerability analysis method described by Susilawati and Taylor [37] – which is firmly embedded in a GIS framework – should produce a valid and practical assessment methodology for network assessment.

7. Conclusions

A recent national forum concerned with research needs on climate change adaptation in Australia [38] devoted a full session to discussions about emergency services planning and management, in which both bushfires and evacuations by road were raised as significant issues for strategic planning, and which demanded increasing attention as the spread and intensity of severe weather events increased under climate change scenarios. In general, the forum concluded that the principal research needs were on reducing uncertainty, and understanding and managing complexity, with emergency management systems better tuned to regional rather than national capacities. The concern was to ensure pro-active planning, using community based approaches, for which the components included risk management, mitigation, adaptation, capabilities, communications, integration and partnerships. 'We can learn today to help tomorrow' was seen as the basic message. The learning process requires support through decision support systems, such as the one outlined above, that can aid the planners and decision makers in emergency service agencies to devise and implement improved plans and strategies to respond to disaster situations. In addition, in an era of demographic change (especially population ageing and migration to peri-urban environments) these systems need to inform land use planning agencies and their processes. There is much scope for transport modellers to provide their specific expertise to valuable ends in these tasks.

8. References

1. Country Fire Service of South Australia: Preparing for bushfires: a guide to home and property protection, http://www.cfs.sa.gov.au
2. Gould, J.: Fire danger and fire behaviour in Australia: overview. Proc. Int. Fire Weather Workshop, Melbourne. Bushfire CRC, Melbourne (2005)
3. Australian Bureau of Meteorology: The exceptional January-February 2009 heatwave in south-eastern Australia. Special Climate Statement 17 (2009)
4. Haynes, K., Tibbits, A., Coates, L., Ganewatta, G., Handmer, J., McAneney, J.: 100 years of Australian civilian bushfire fatalities: exploring the trends in relation to the 'stay or go policy'. Report for the Australian Bushfire Cooperative Research Centre, Melbourne (2008)

5. Bureau of Transport Economics: Economic costs of natural disasters in Australia. Report 103, Bureau of Transport, Infrastructure and Regional Economics, (2001)
6. WA Department of Environment and Conservation: Fire as a management tool. www.dec.wa.gov.au/fire.prescribed-burning/fire-as-a-management-tool/managing-wildfire-risk
7. Government of Alberta: Using Fireweb to complete a power line hazard assessment plan (PHAP) for utility industry clients. Appendix A: Using the following Wildfire Threat Assessment maps for your powerline hazard assessment plan, (2007), www.srd.gov.ab.ca/wildfires/information/usingfirewebutility.aspx
8. Cary, G.: FIRE! The Australian experience. *Proc. National Academies Forum*, University of Adelaide, Adelaide (1999)
9. Kirvan, A.: Quantification of wildfire risk in south-west Western Australia, Unpublished PhD thesis, University of Western Australia, Perth (2005)
10. Tolhurst, K., Shields, B., Chong, D.: Phoenix: development and application of a bushfire risk management tool. *Aust. J. Emergency Management* 23 (4), 47—54 (2008)
11. McArthur, A.G.: Fire behaviour in eucalypt forests, Commonwealth of Australia Forest and Timber Bureau, Leaflet Number 107, (1967)
12. CSIRO: http://www.csiro.au/products/Mk5ForestfireDangerMeter.html
13. CSIRO: http://www.csiro.au/products/Grass-Fire-Danger-Meter.html
14. Krusel, N., Petris, S.: A study of civilian deaths in the 1983 Ash Wednesday bushfires Victoria, Australia. CFA Occasional Paper No 1. Country Fire Authority of Victoria (1999)
15. Alsnih, R., Rose, J., Stopher, P.R.: Dynamic travel demand for emergency evacuation: the case of bushfires. *Papers of the Australasian Transport Research Forum* 27 [available at www.patrec.org/atrf.aspx] (2004)
16. Sorensen, J.H., Vogt, B., Mileti, D.S.: Evacuation: an assessment of planning and research. Oak Ridge National Laboratory, Report to the Federal Emergency Management Agency, Washington D.C. (1987)
17. Fu, H., Wilmot, C.G.: Sequential logit dynamic travel demand model for hurricane evacuation. *Transpn. Res. Rec.* 1882, 19—26 (2004)
18. Mozumder, P., Raheem, N., Talberth, J., Berrens, R.P.: Investigating intended evacuation from wildfires in the wildland-urban interface: application of a bivariate probit model. *Forest Pol. & Eco.* 10 (6), 415—423 (2008)
19. Russo, F., Chila, G.: Safety of users in road evacuation: RP vs SP surveys in demand analysis. In: Brebbia, C A (ed.) *Urban Transport XIV - Urban Transport and the Environment in the 21st Century*, pp. 703-713. WIT Press, Southampton (2008)
20. Lindell, M.K.: EMBLEM2: An empirically based large scale evacuation time estimate model. *Transpn. Res. A* 42 (1), 140—154 (2008)
21. Yazici, M.A., Ozbay, K.: Evacuation modelling in the United States: does the demand model choice matter? *Transp. Rev.* 28 (6), 757—779 (2008)
22. Ahola, T., Virrantaus, K., Krisp, J.M., Hunter, G.J.: A spatio-temporal population model to support risk assessment and damage analysis for decision-making. *Int. J. Geog. Info. Sc.* 21 (8), 935—953 (2007)
23. Arnol, C.: Firefighting operations on the urban interface. Fellowship Report 20081. The Winston Churchill Memorial Trust of Australia, Canberra. (2007)
24. Victorian Bushfires Royal Commission: Interim report July 2009 of the Victorian Bushfires Royal Commission. Melbourne. www.royalcommission.vic.gov.au/Public-Hearings/SUB-100-001-0001
25. Paveglio, T. Carroll, M.S., Jakes, P.J.: Alternatives to evacuation – protecting public safety during wildland fire. *J. Forestry* 106 (2), pp.65--70 (2008)
26. Australian Bureau of Meteorology: Severe weather events in Victoria: bushfires in Victoria, 7-8 February 2009, http://www.bom.gov.au
27. Radwan, A.E., Hobeika, A.G., Sivasailam, D.: A computer-simulation model for rural network evacuation under natural disasters. *ITE J.* 55 (9), 25-30 (1985)
28. Church, R.L., Cova, T.J: Mapping evacuation risk on transportation networks using a spatial optimization model. *Transpn. Res. C* 8 (1-6), 321—336 (2000)
29. Sohn, J.: Evaluating the significance of highway network links under the flood damage: an accessibility approach. *Transpn. Res. A* 40 (6), 491—506 (2006)
30. Yuan, F., Han, L.D., Chin, S.M., Hwang, H.L.: Proposed framework for simultaneous optimization of evacuation traffic destination and route assignment. *Transpn. Res. Rec.* 1964, 50--58 (2006)
31. Murray-Tuite, P.: Perspectives for network management in response to unplanned disruptions. *ASCE J. Urb. Plan. & Devel.* 133 (1), 9--17 (2007)
32. Laval, J.A: A macroscopic theory of two-lane rural roads. *Transpn. Res. B* 40, 937--944 (2006)
33. Hoogendoorn, S.P.: Unified approach to estimating free speed distributions. *Transpn. Res. B* 39, 709–727 (2005)
34. Jenelius, E., Petersen, T., Mattsson, L-G.: Importance and exposure in road network vulnerability analysis. *Transpn. Res. A* 40, 537--560 (2006)
35. Taylor, M.A.P., Sekhar, S.V.C., D'Este, G.M.: Application of accessibility based methods for vulnerability analysis of strategic road networks. *Netw. & Spat. Econ.* 6 (3-4), pp.267--291 (2006)
36. Taylor, M.A.P.: Critical transport infrastructure in urban areas: impacts of traffic incidents assessed using accessibility based network vulnerability analysis. *Growth and Change* 39 (4), 593—616 (2008)
37. Susilawati, S., Taylor, M.A.P.: An accessibility approach in assessing regional road network vulnerability. *Papers of the Australasian Transport Research Forum* 27 [available at www.patrec.org/atrf.aspx] (2008)
38. National Climate Change Adaptation Research Facility: NCCARF Symposium 2009: the first national forum of the National Climate Change Adaptation Research Facility, http://www.nccarf.edu.au